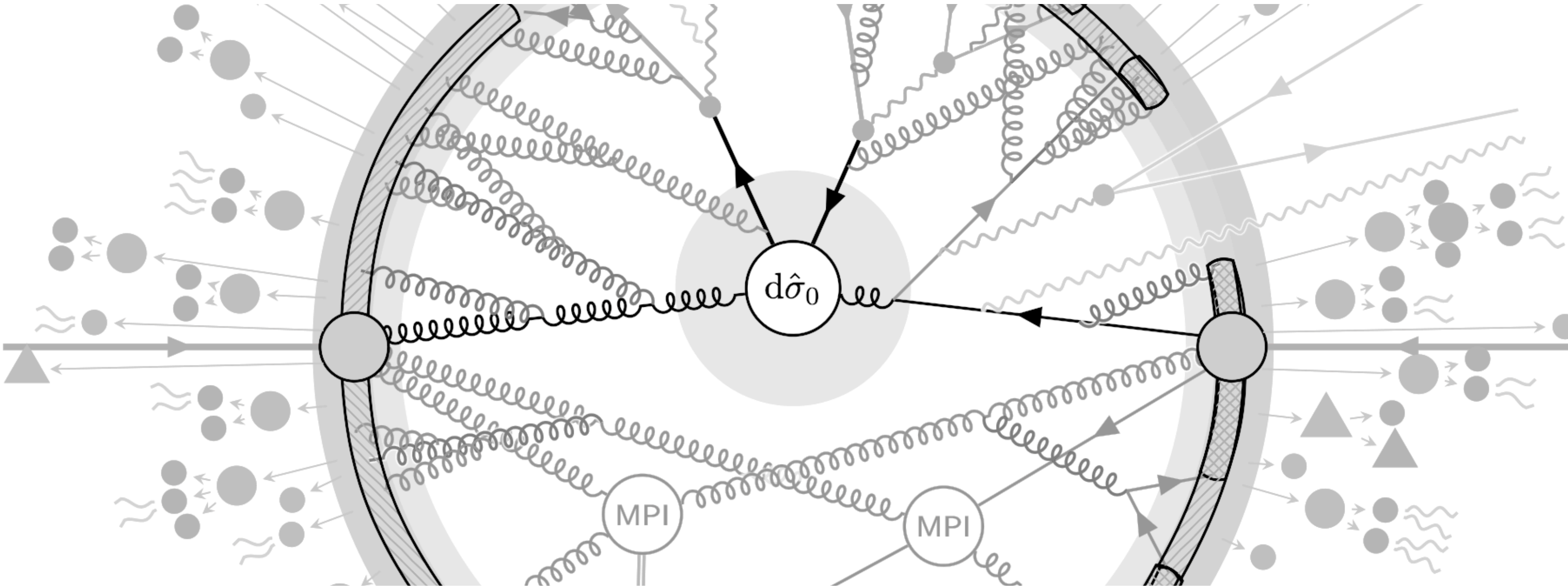
Anatomy of Hadron Collisions — and Future Challenges

Peter Z Skands — University of Oxford & Monash University — CERN, March 2024



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MONASH WARWICK ALLIANCE
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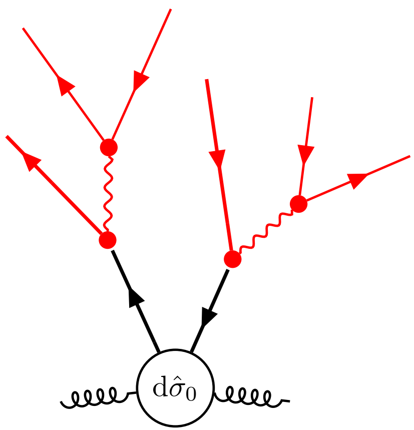
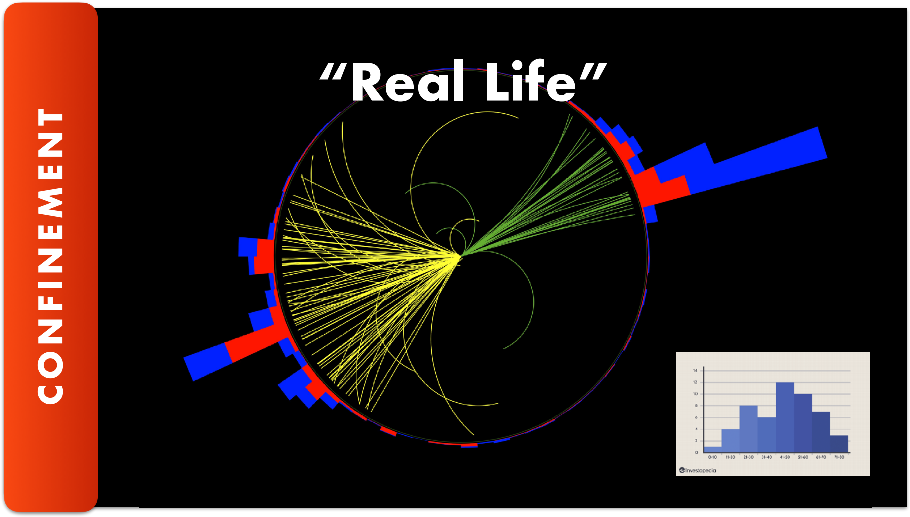
The Goal

Use LHC measurements to test hypotheses about Nature

Problem 1: no **exact** solutions to QFT
➜ Perturbative **Approximations**



Elementary Fields,
Symmetries,
Interactions



Problem 2: Confinement
We collide — and observe – **hadrons**

The Goal

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Problem 1: no **exact** solutions to QFT
➜ Perturbative **Approximations**

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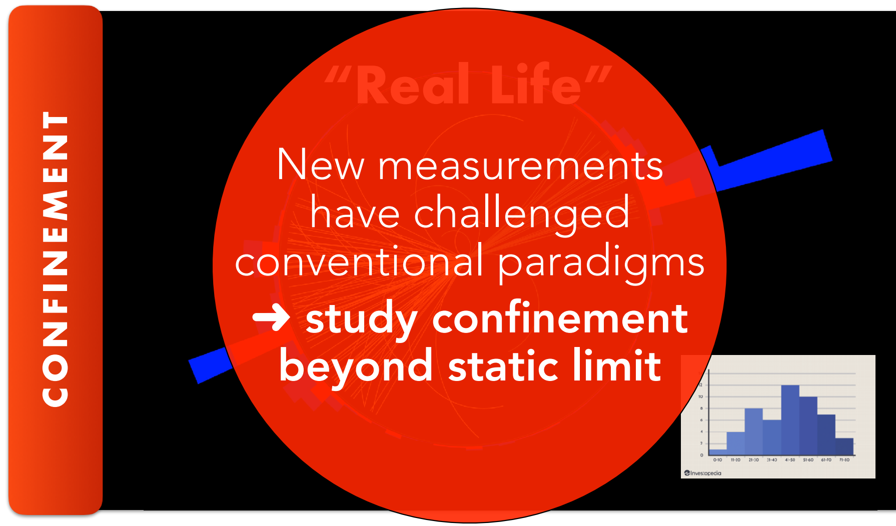
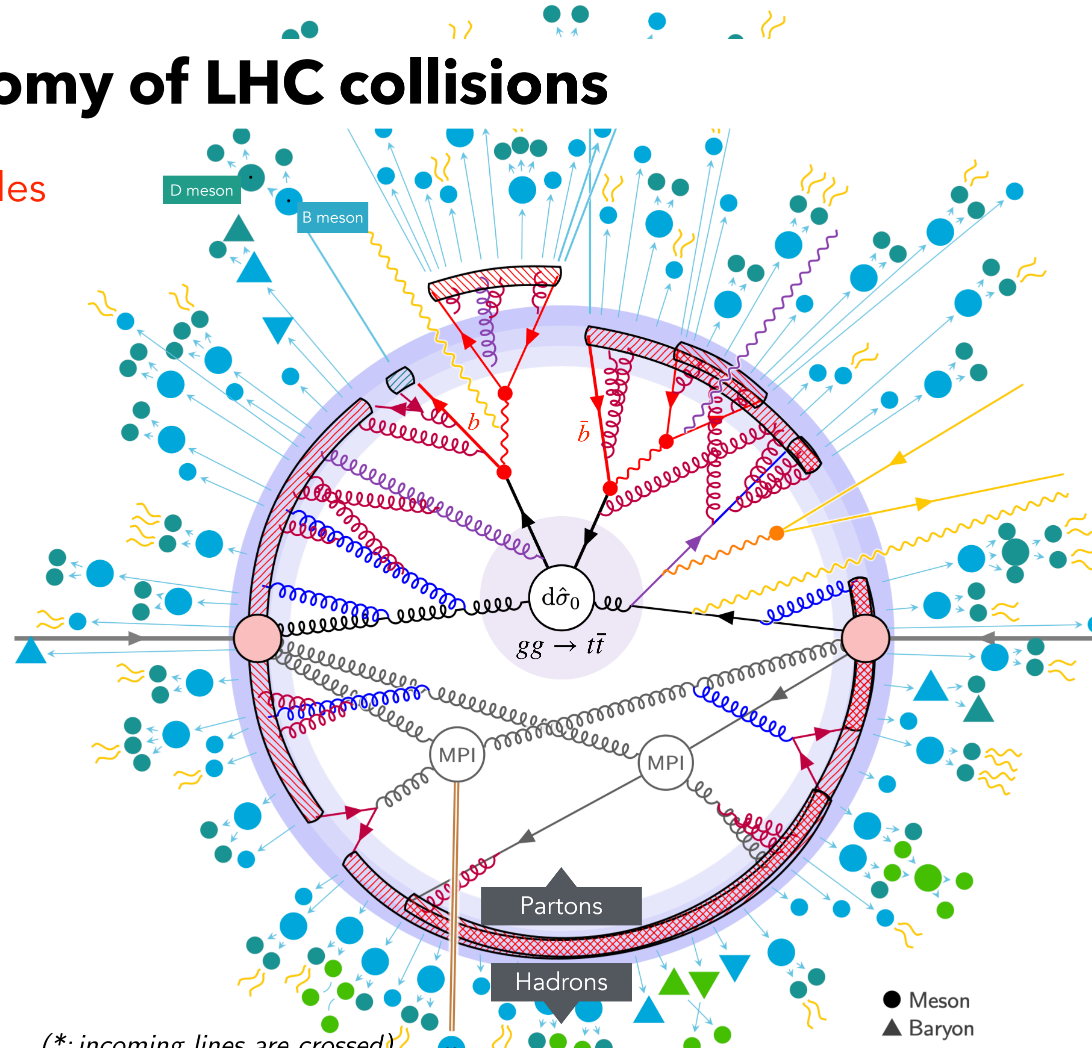


Problem 2: Confinement
We collide — and observe – **hadrons**

Anatomy of LHC collisions

Physics Separation of scales

Maths Factorizations



(: incoming lines are crossed)*

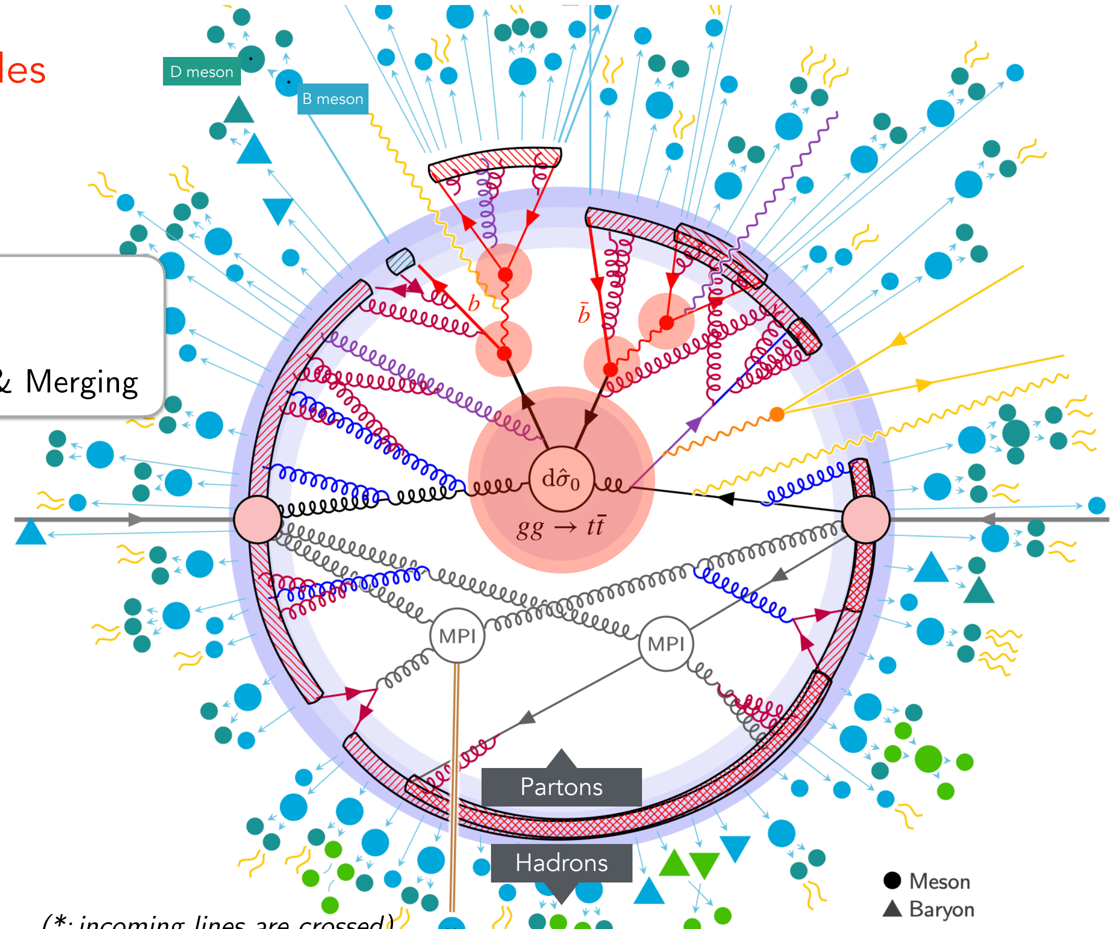
[Figure from Bierlich et al., SciPost Phys.Codeb. 2022 (2022) 8 arXiv:2203.11601]

Hard Process & Fixed-Order Corrections

Physics Separation of scales

Maths Factorizations

Hard Process	Hard Interaction Resonance Decays MECs, Matching & Merging



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[Figure from Bierlich et al., SciPost Phys.Codeb. 2022 (2022) 8 arXiv:2203.11601]

Infinite-Order Perturbative Corrections

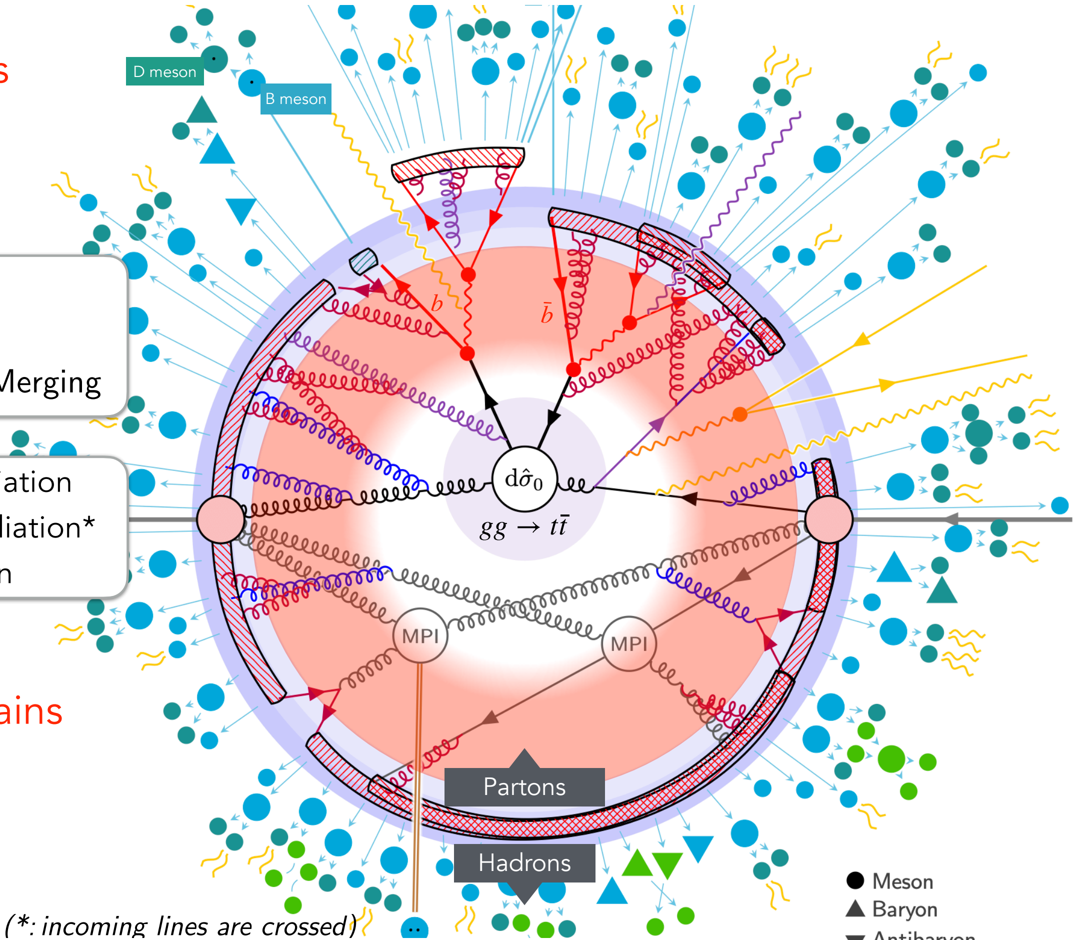
Physics Separation of scales

Maths Factorizations

Hard Process
- ◯ Hard Interaction
- ● Resonance Decays
- ■ MECs, Matching & Merging

Parton Showers
- ■ QCD Final-State Radiation
- ■ QCD Initial-State Radiation*
- ■ Electroweak Radiation

Algorithms Nested Markov Chains



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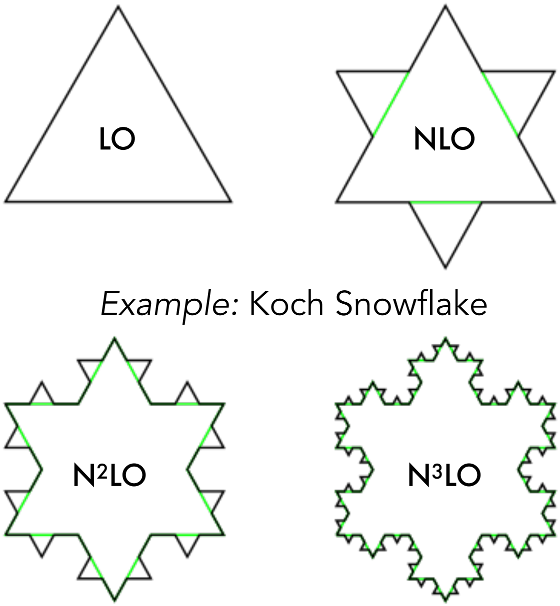
[Figure from Bierlich et al., SciPost Phys.Codeb. 2022 (2022) 8 arXiv:2203.11601]

Perturbative Approaches

P.T. ~ Calculate the area of a shape ($d\sigma$) with higher and higher detail

Difference from exact area $\propto \alpha^{n+1}$

Fixed Order



Example: Koch Snowflake

Note: (over)simplified analogy, mainly for IR structure. More at each order than shown here.

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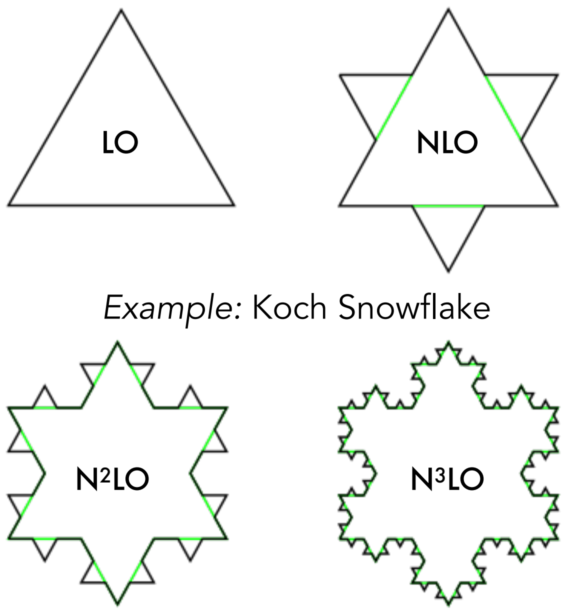
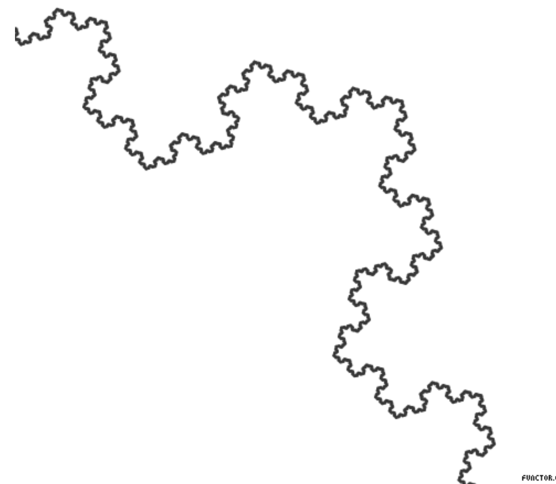


Example: Koch Snowflake

Resummation



Massless gauge theories

Scale invariance ➜ fractal substructure

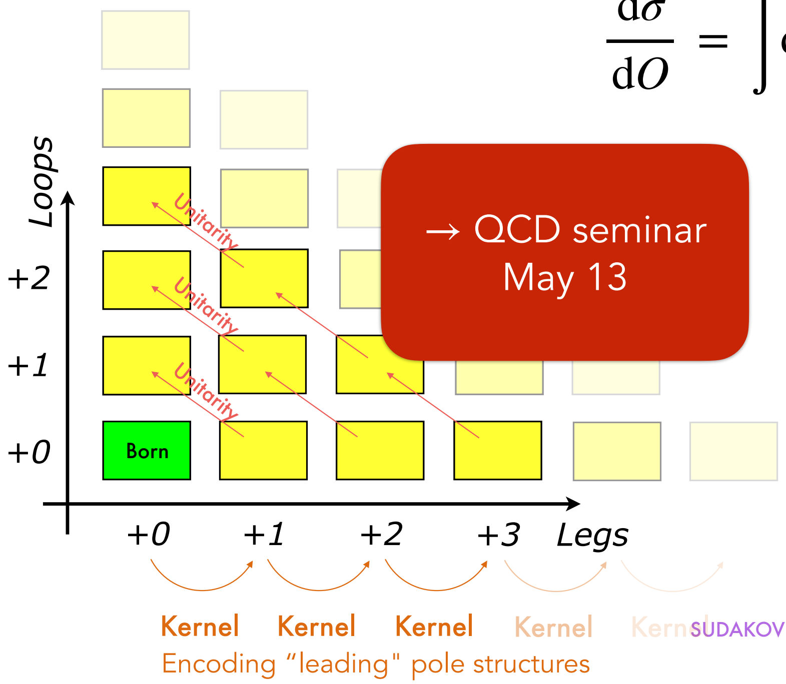
(+ not hard to build in running coupling)

Note: (over)simplified analogy, mainly for IR structure. More at each order than shown here.

Perturbation Theory as a Markov Chain

Stochastic differential evolution in "hardness" scale

$\mathrm{d}\sigma$ for generic observable "O", expressed as a Markov chain:



→ QCD seminar May 13

$$\frac{\mathrm{d}\sigma}{\mathrm{d}O} = \int \mathrm{d}\Phi_0 \underbrace{|M_{\mathrm{Born}}|^2 (1 + F_{\mathrm{NLO}} + \ldots)}_{\text{Fixed–Order Matching Coefficients}} \underbrace{\mathcal{S}(\Phi_0, O)}_{\text{Shower}}$$

$$\mathcal{S}_{+1}(\Phi_n, O) = \overbrace{\Delta(\Phi_n, Q_{\mathrm{IR}})}^{\text{'Sudakov Factor'}} \overbrace{\delta\left(\hat{O}(\Phi_n) - O\right)}^{\text{Evaluate } O \text{ on } \Phi_n}$$

$$+ \int \mathrm{d}\Phi_{+1} \overbrace{\Delta(\Phi_n, Q_{n+1})}^{\text{Sudakov Factor}} \overbrace{\frac{|M_{n+1}|^2}{|M_n|^2}}^{\text{Branching Kernel}} \mathcal{S}(\Phi_{n+1}, O)$$

MARKOV CHAIN

UNITARITY

SUDAKOV FACTOR $\Delta(\Phi_n, Q) = \exp\left(-\int_{Q^2}^{Q_n^2} \mathrm{d}\Phi_{+1} \frac{|M_{n+1}|^2}{|M_n|^2}\right)$

Why go beyond **Fixed-Order** perturbation theory?

Fixed-Order calculations most accurate for single-scale problems

Effective accuracy reduced for processes/observables with **scale hierarchies**

Schematic example:

NNLO calculation of the rate of events passing a **jet veto:**

$$\overbrace{F_0}^{\text{LO}} + \overbrace{\alpha_s(L^2 + L + F_1)}^{\text{NLO}} + \overbrace{\alpha_s^2(L^4 + L^3 + L^2 + L + F_2)}^{\text{NNLO}}$$

$L \propto \ln(p_{\perp\text{veto}^2} / Q^2_{\text{hard}})$ — arising from integrals over propagators $\propto \frac{\mathrm{d}p_\perp^2}{p_\perp^2}\mathrm{d}y$

Total loss of predictivity for $p_{\perp\text{veto}} \ll Q_{\text{hard}} \Longrightarrow \alpha_s L^2 \sim 1$.

Reduced precision even for higher veto scales. **Logs counteract naive suppression.**

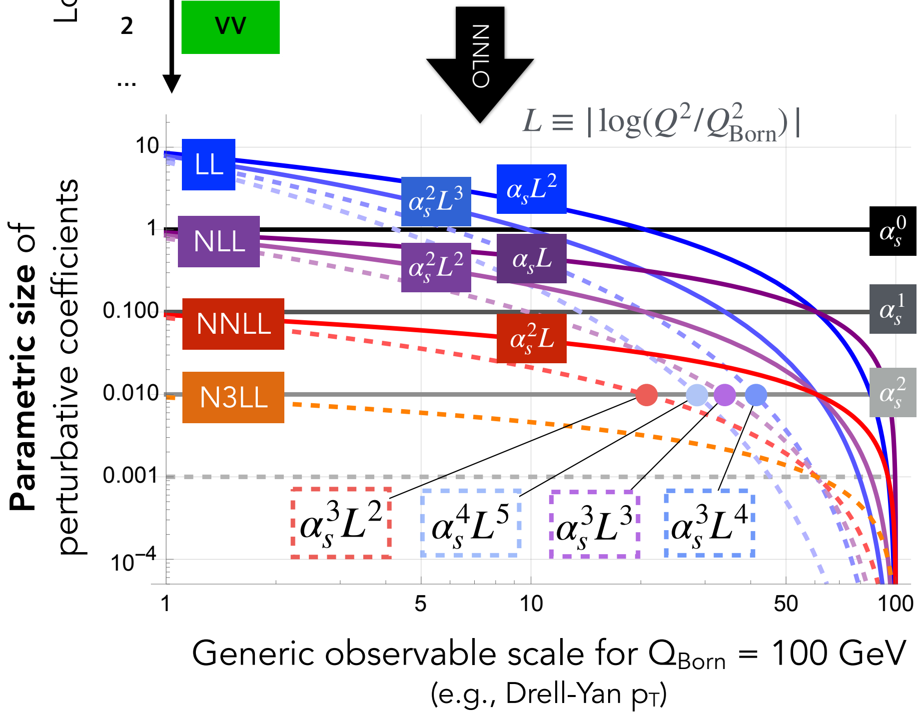
The Case for **Embedding** Fixed-Order Calculations **within Showers**

NNLO

Loops \ Legs	0	1	2	3	…
0	B	R	RR		
1	V	RV			
2	VV				
…					

+ Showers

Loops \ Legs	0	1	2	3	…
0	B	PS_1	PS_2	PS_3	…
1	$B\cdot\Delta_B^1$	$PS_1\cdot\Delta_1^1$	$PS_2\cdot\Delta_2^1$	$PS_3\cdot\Delta_3^1$	…
2	$B\cdot\Delta_B^2$	$PS_1\cdot\Delta_1^2$	$PS_2\cdot\Delta_2^2$	…	
…	…	…	…		



Resummation extends domain of validity of perturbative calculations

Showers ➤ Fully exclusive final states

➜ can model non-perturbative physics, full-event analyses, fiducial cuts, …

Target for next generation of MCs:

%-level precision @ LHC

⇒ NNLO + NNLL

Not quite there yet — but close …

Warmup: NLO + Shower with POWHEG

Nason 2004;
Fixione, Nason, Oleari 2007

(Just focusing on the real-radiation part)

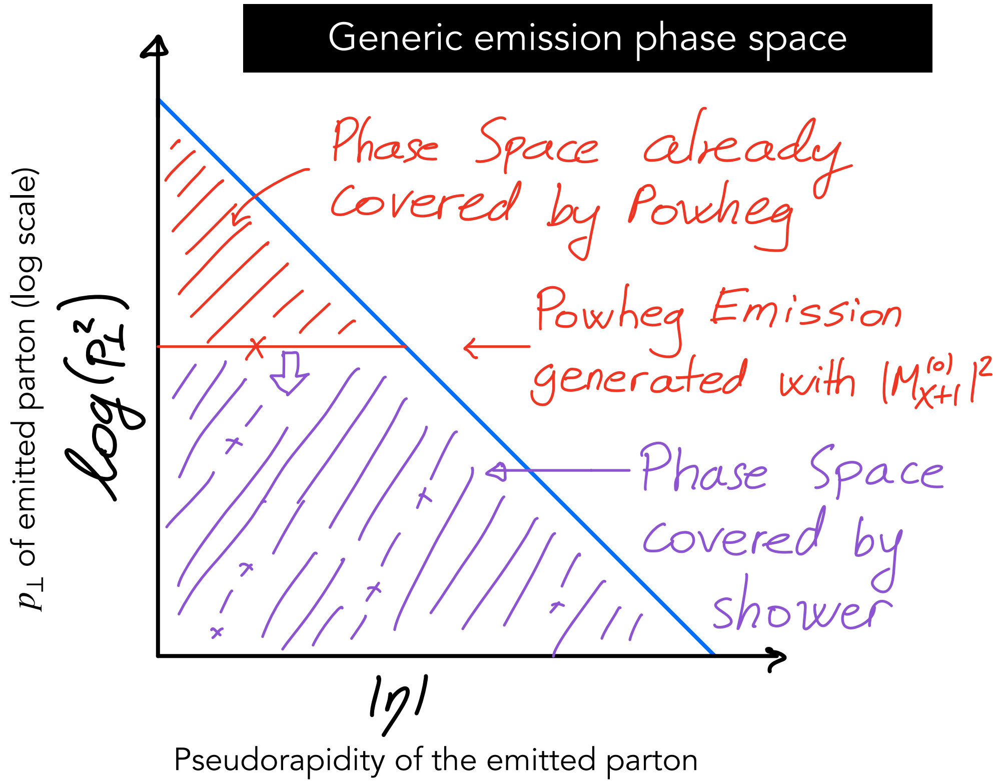
POWHEG generates hardest emission in a shower-like manner (MECs)

Matrix-Element Corrections (MECs)
[Bengtsson & Sjöstrand 1987 + …]

+ NLO Born Normalization
[Nason 2004; Fixione, Nason, Oleari 2007]

Sweeping over phase space, from high to low p_T

Shower then takes over and generates all further emissions



Powheg Box — A Subtlety

[Alioli et al, 2010]

Industry Standard: "Powheg Box"

Exploits having its own definition of "p_T"

$\neq$ shower's definition of p_T

Breaks clean matching

Solution: Vetoed Showers

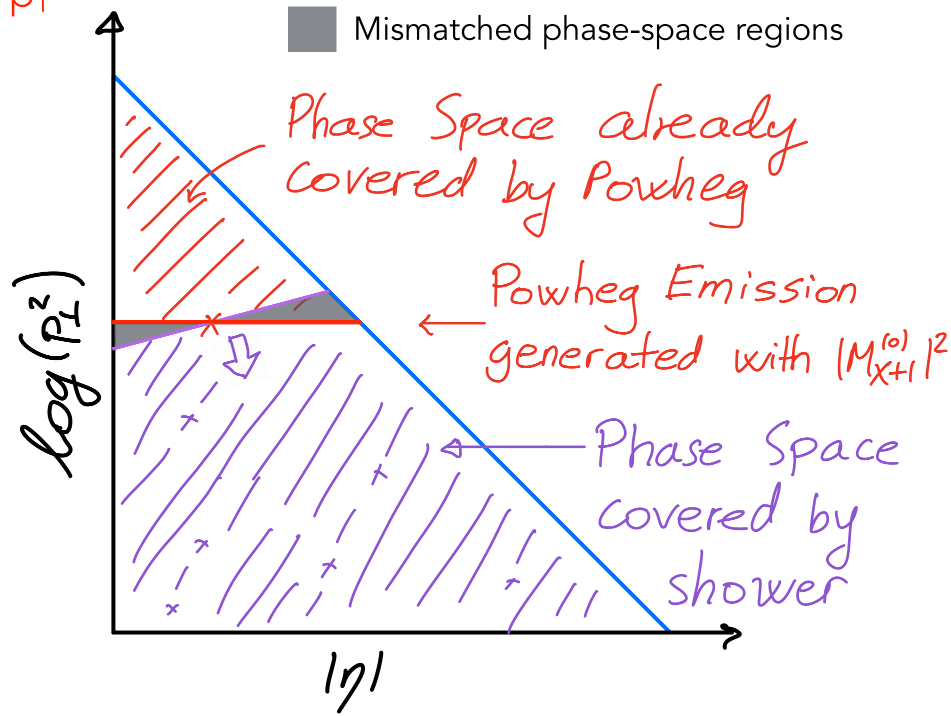
(+ truncated showers)

Works very well for simple cases

Induces an uncertainty/ambiguity

Purely associated with the matching scheme (not physical)

Can be important for complex / multi-scale processes.



E.g., Nason, Oleari arXiv:1303.3922

VBF: Höche et al., SciPost Phys. 12 (2022) 1

2. From NLO to NNLO

MiNNLO$_{PS}$ builds on (extends) POWHEG NLO for X + jet

[Hamilton et al. 1212.4504, Monni et al. 1908.06987]

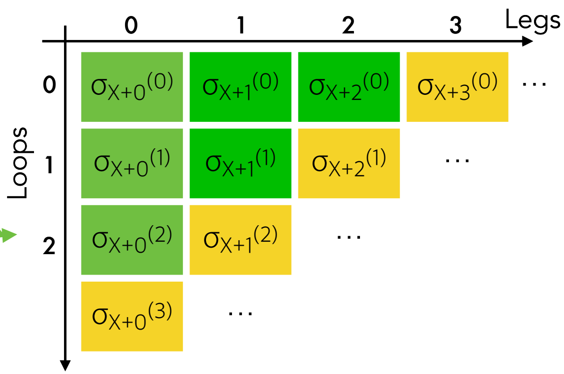
Allow the first jet to approach $p_\perp \to 0$ ~ X + 0

Tame divergence with analytic (NNLL) Sudakov

(introduces additional hardness scale = resummation scale)

Normalize inclusive $d\sigma_X$ to NNLO

($\mathcal{O}(\alpha_s^3)$ ambiguity on how to "spread" the additional contributions in phase space.)



~ Best you can do with current off-the-shelf parton showers

Is approximate; introduces some ambiguities:

$p_\perp^{\text{Shower}}$ vs $p_\perp^{\text{Powheg}}$ vs $Q_{NNLL}^{\text{resummation}}$ & differential NNLO spreading

(+ possible efficiency bottleneck: $p_\perp \to 0$ singularity × Sudakov veto)

What if we could lift that restriction?

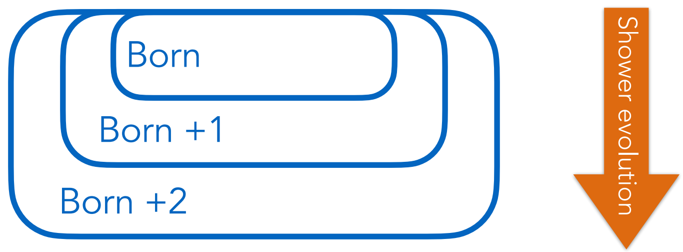
Towards True* NNLO Matching

*In the sense of the fixed-order and shower calculations matching each other point by point in each phase space

Idea: Use (nested) Shower Markov Chain as NNLO Phase-Space Generator

Harnesses the power of showers as efficient phase-space generators for QCD

Pre-weighted with the (leading) QCD singular structures = soft/collinear poles



Different from conventional Fixed-Order phase-space generation (eg VEGAS)

Towards True* NNLO Matching

*In the sense of the fixed-order and shower calculations matching each other point by point in each phase space

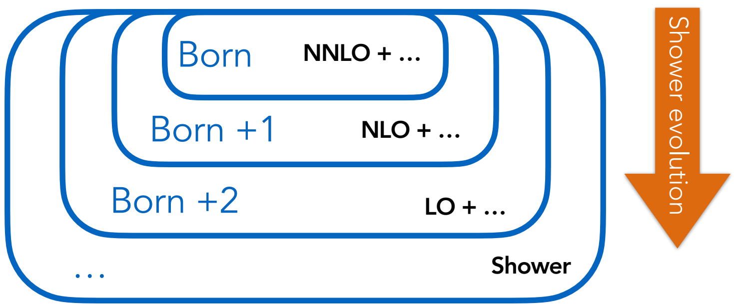
Continue shower afterwards

No auxiliary / unphysical scales

⇒ expect small matching systematics

(arXiv:2108.07133 & arXiv:2310.18671)

→ QCD seminar May 13



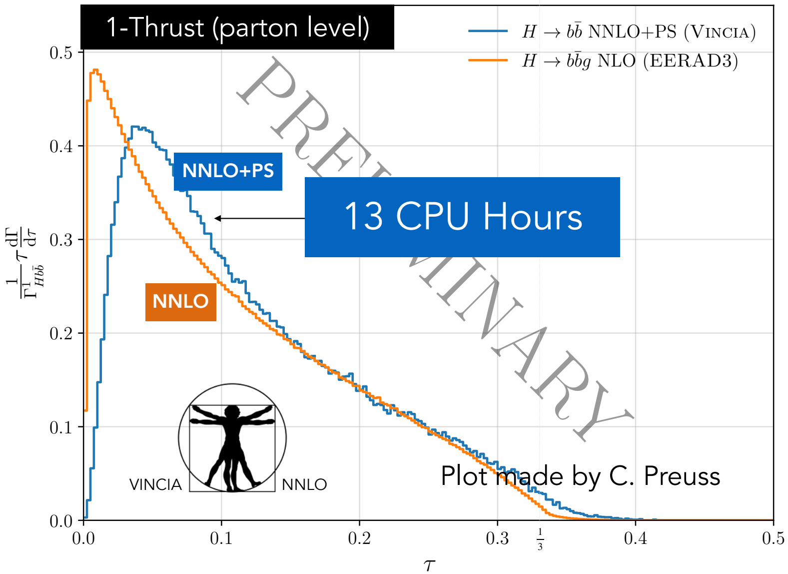
Need:

1. Born-Local NNLO ($\mathcal{O}(\alpha_s^2)$) K-factors: $k_{\mathrm{NNLO}}(\Phi_2)$
2. NLO ($\mathcal{O}(\alpha_s^2)$) MECs in the first $2 \to 3$ shower emission: $k_{\mathrm{NLO}}^{2\to3}(\Phi_3)$
3. LO ($\mathcal{O}(\alpha_s^2)$) MECs for next (iterated) $2 \to 3$ shower emission: $k_{\mathrm{LO}}^{3\to4}(\Phi_4)$
4. Direct $2 \to 4$ branchings for unordered sector, with LO ($\mathcal{O}(\alpha_s^2)$) MECs: $k_{\mathrm{LO}}^{2\to4}(\Phi_4)$ NEW

VINCIA NNLO

Preview: VINCIA NNLO+PS for $H \to b\bar{b}$

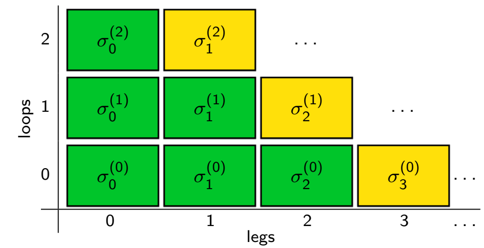
VINCIA NNLO



"NNLO" Reference = **EERAD3** NLO $H \to b\bar{b}g$

[Coloretti, Gehrmann-de Ridder, Preuss, JHEP 06 (2022) 009]

NNLO accuracy in $H \to 2j$ implies **NLO correction in first emission** and **LO correction in second emission.**



So for Thrust, NNLO $H \to b\bar{b}$ is effectively

NLO for $\tau < 1/3$

LO for $\tau > 1/3$

VINCIA NNLO+PS: shower as phase-space generator: efficient & no negative weights!

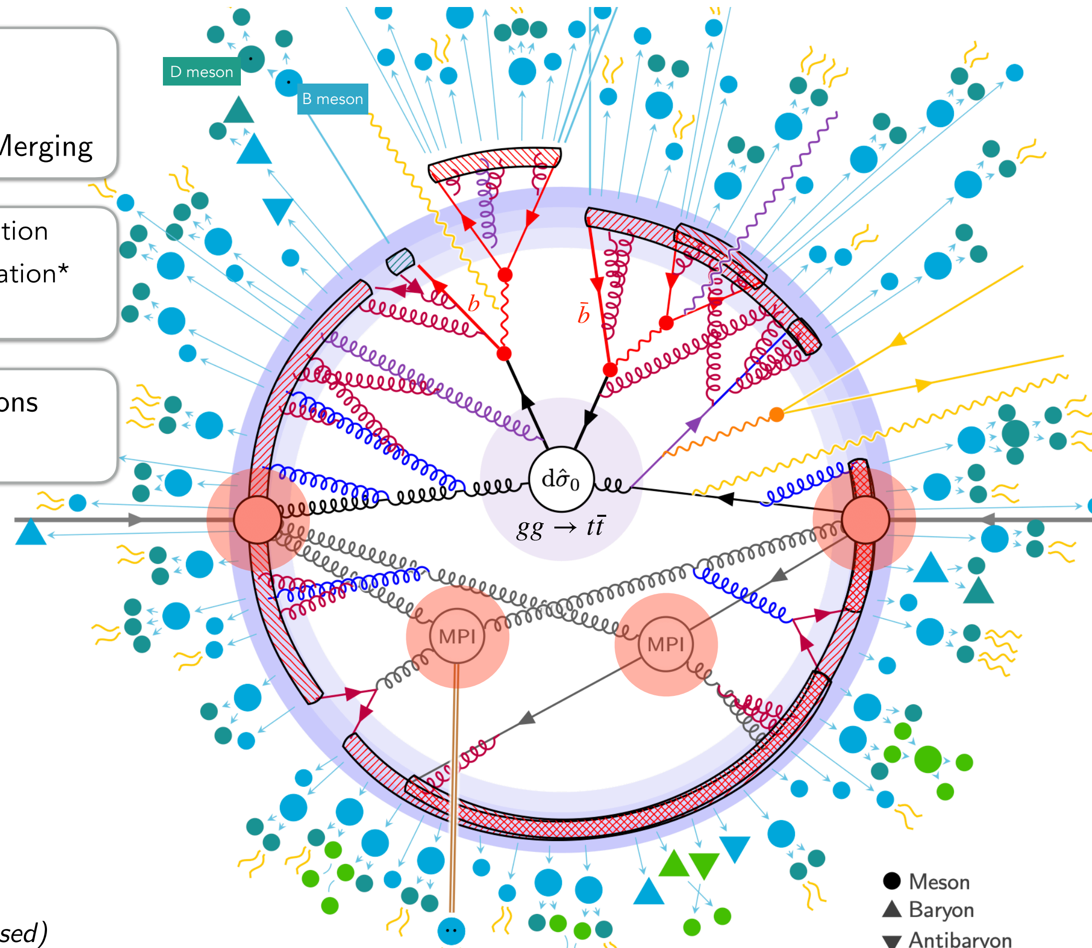
- Looks ~ 5 x ***faster*** than **EERAD3** (for equivalent unweighted stats)

+ is **matched to shower** (add shower resummation without auxiliary input/scales) + can be **hadronized**

Proof of concepts now done for $Z/H \to q\bar{q}$; work remains for pp (& for N^{n}LL accuracy)

Part II – Nonperturbative Aspects

Hard Process	◯ Hard Interaction ● Resonance Decays ■ MECs, Matching & Merging
Parton Showers	■ QCD Final-State Radiation ■ QCD Initial-State Radiation* ■ Electroweak Radiation
Underlying Event	◯ Multiparton Interactions □ Beam Remnants*



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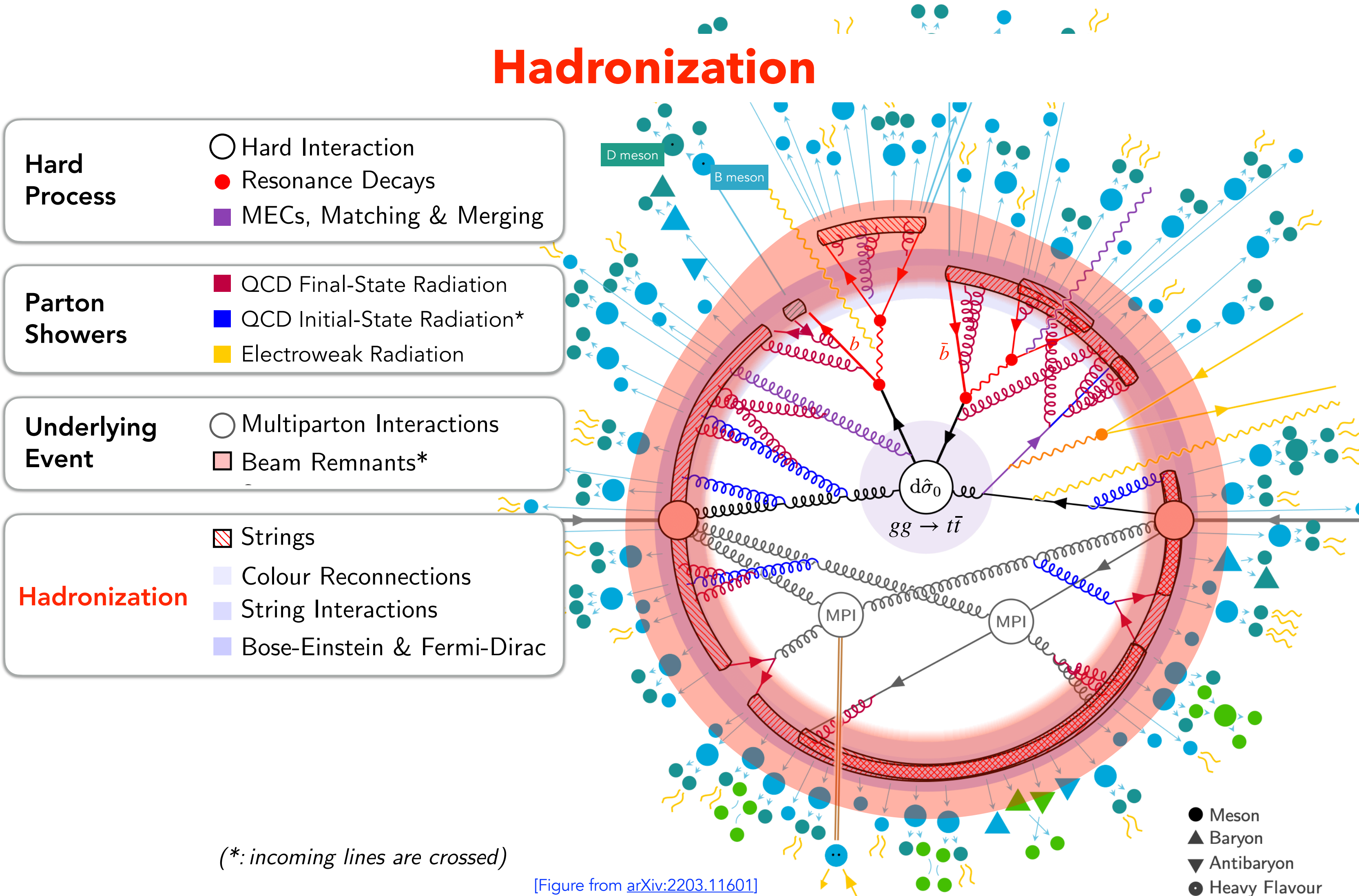
[Figure from arXiv:2203.11601]

Hadronization



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Hadron Decays

Hard Process	◯ Hard Interaction ● Resonance Decays ■ MECs, Matching & Merging
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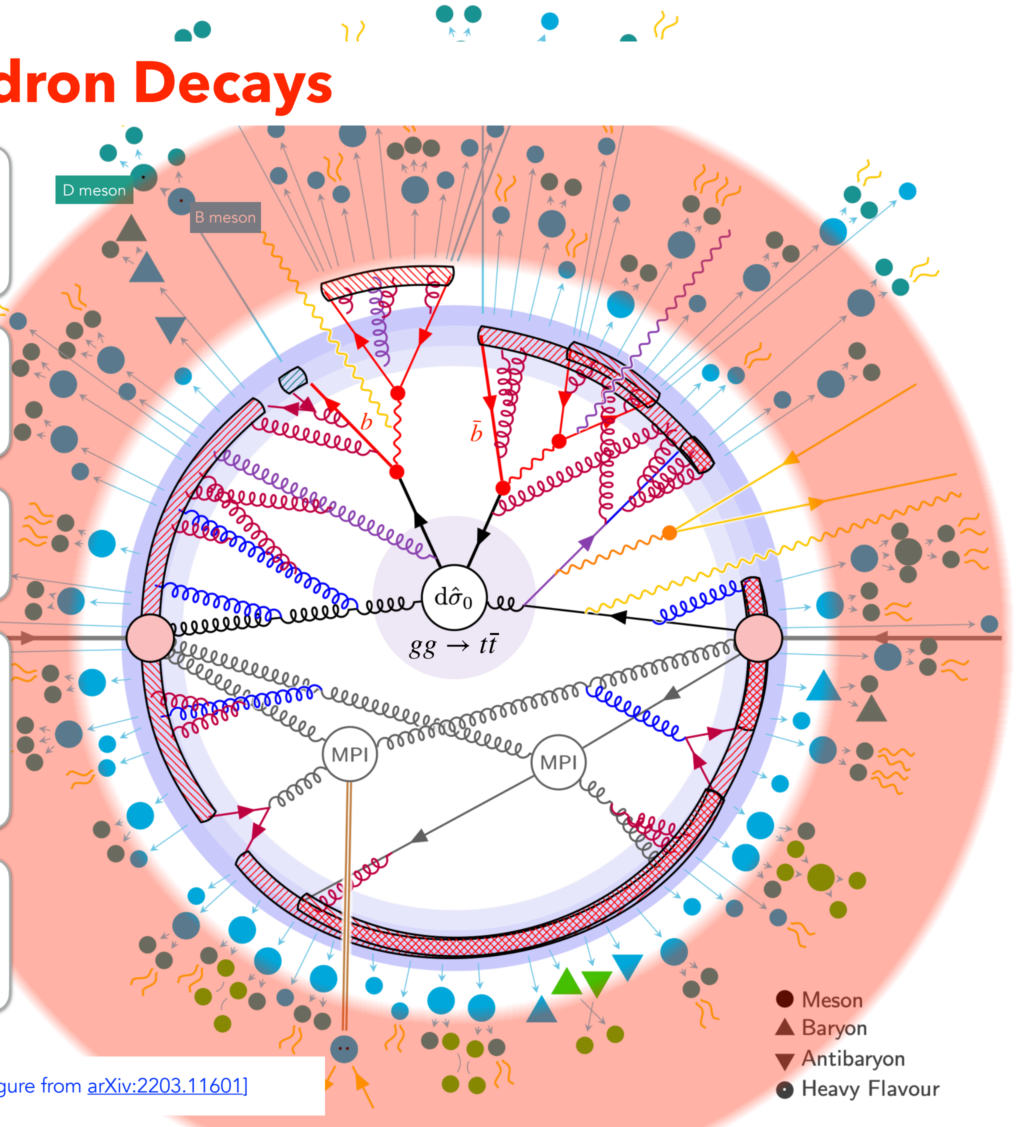
Hadronization	Strings Colour Reconnections String Interactions Bose-Einstein & Fermi-Dirac
Hadron (& τ) Decays	■ Primary Hadrons ■ Secondary Hadrons ■ Hadronic Reinteractions

(: incoming lines are crossed)*

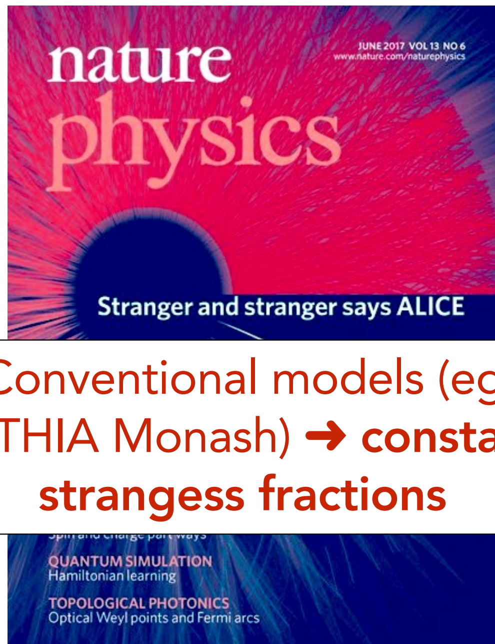


[Figure from arXiv:2203.11601]

New Discoveries in Hadronization

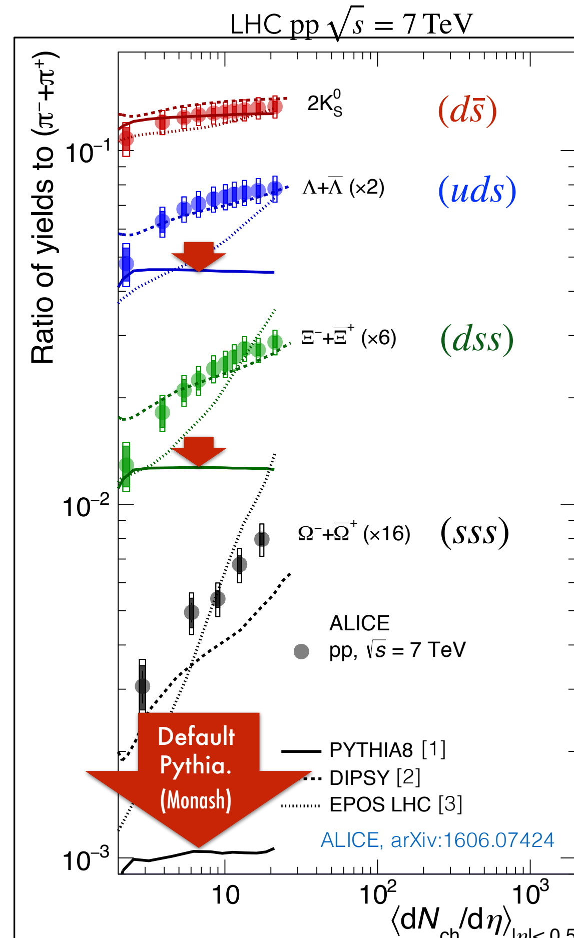
What a strange world we live in, said ALICE

Ratios of strange hadrons to pions strongly increase with event activity



June 2017

Conventional models (eg PYTHIA Monash) ➜ **constant strangess fractions**



New Discoveries in Hadronization

LHC experiments also report very large (factor-10) enhancements in heavy-flavour baryon-to-meson ratios at low p_T!

Conventional models (eg PYTHIA Monash) ➜ **constant baryon-to-meson ratio**

(Just showing Λ_c^+ here; same pattern for other heavy-flavour baryons & also seen by LHCb)

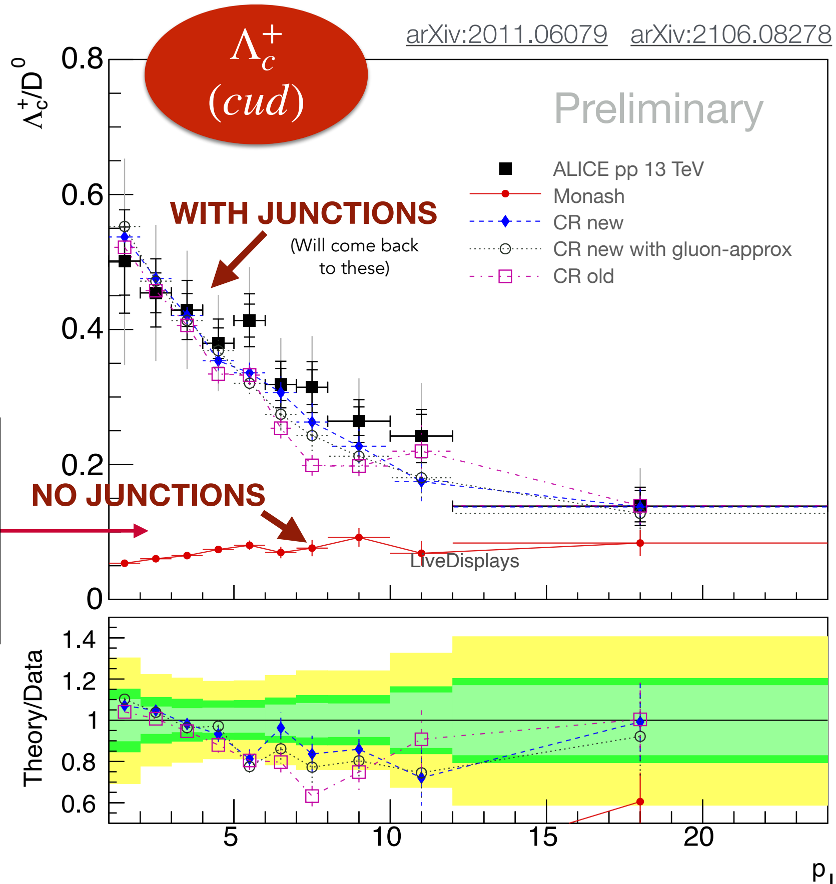
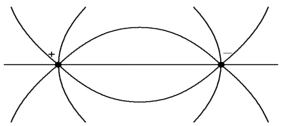


Figure from Altmann & **PZS**, *String Junctions Revisited*, in progress

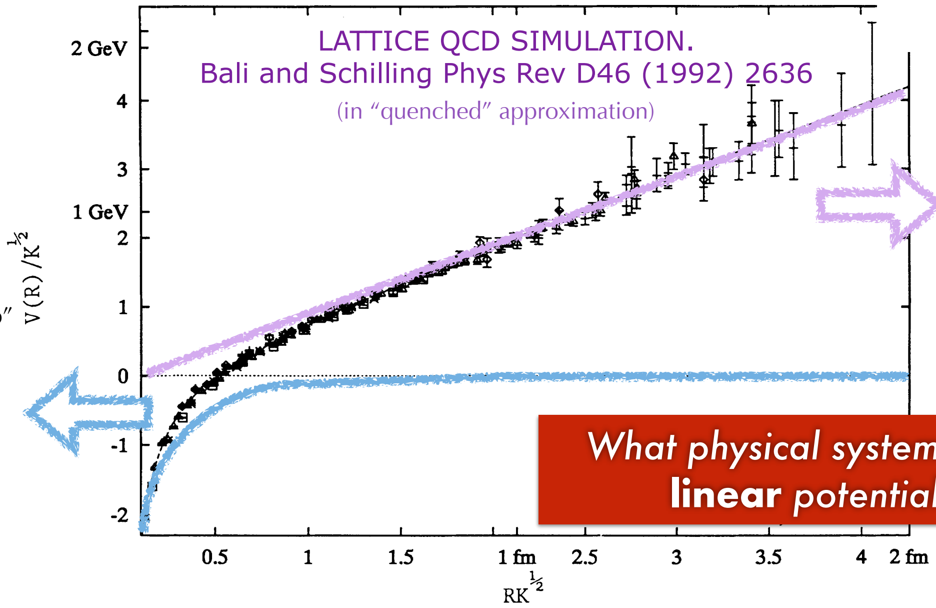
Back to Basics — Anatomy of (Linear) Confinement

On lattice, compute potential energy of a colour-singlet $q\bar{q}$ state, as function of the distance, r, between the q and $\bar{q}$

Short Distances ~ "Coulomb"



"Free" Partons



What physical system has a* linear *potential?

Long Distances ~ Linear Potential

"Confined" Partons
(a.k.a. Hadrons)

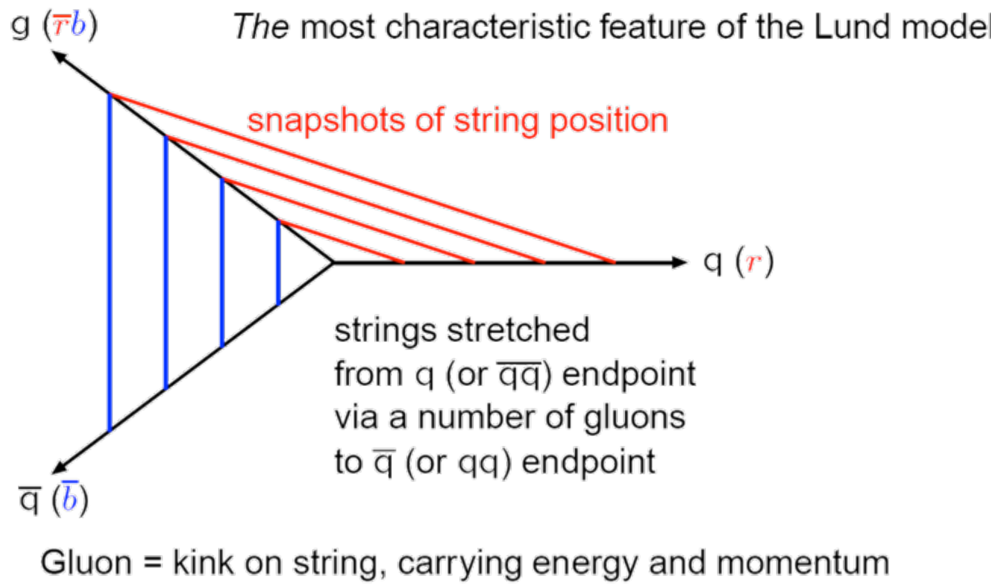
"Cornell Potential" fit: $V(r) = -\frac{a}{r} + \kappa r$ with $\kappa \sim 1\ \mathrm{GeV/fm}$

From Partons to Strings

Map:

Quarks → String Endpoints

Gluons → Transverse Excitations (kinks)



Physics then in terms of string worldsheet evolving in spacetime

"Nambu-Goto action" $\Longrightarrow$ Area Law.

String Breaking

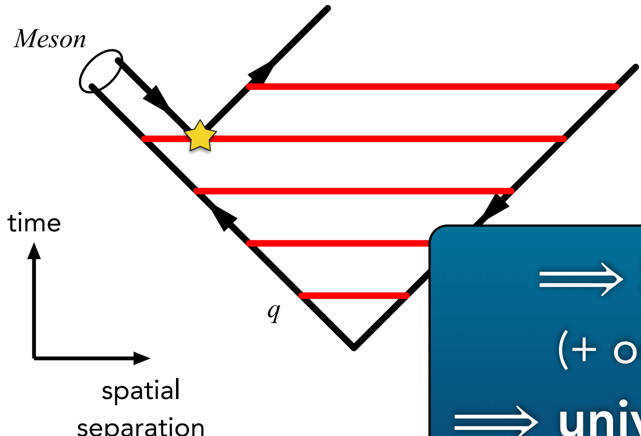
Non-perturbative $g \to q\bar{q}$

$\Longrightarrow$ The strings will "break"

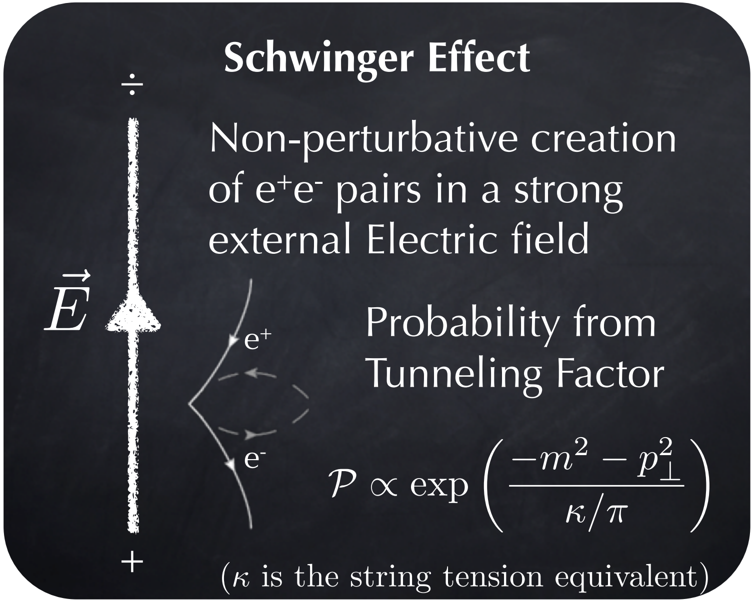
Non-perturbative so can't use $P_{g\to q\bar{q}}(z)$

Our model: Schwinger mechanism →

Assume const probability per unit world-sheet area:



J. Schwinger, Phys. Rev. **82** (1951) 664



$\Longrightarrow$ **Suppression** of m_s^2/κ relative to $m_{u,d}^2/\kappa$

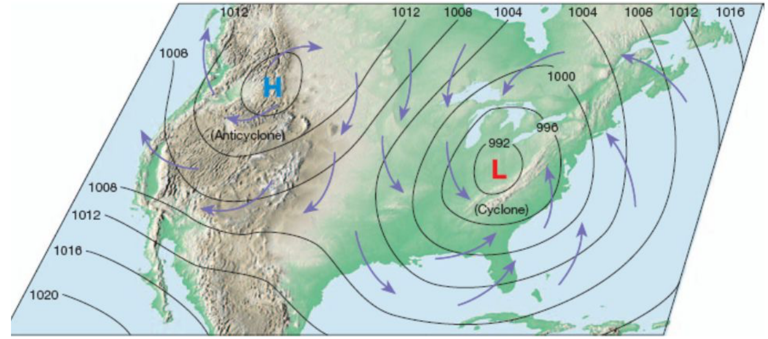
(+ occasionally get a "diquark" too ➜ baryons)

$\Longrightarrow$ **universal (constant) ratios** (for constant m, κ)

Beyond the Static Limit

Regard tension κ as an emergent quantity?
Not fundamental strings

Cyclonic and Anticyclonic Winds



May depend on (invariant) time τ

E.g., hot strings which cool down

Hunt-Smith & **PZS** EPJC 80 **(2020)** 11

May depend on σ (excitations)

Working with E. Carragher & J. March-Russell in Oxford.

May depend on environment (e.g., other strings nearby)

Two approaches (so far) within Lund string-model context:

Colour Ropes [Bierlich, Gustafson, Lönnblad, Tarasov JHEP 03 **(2015)** 148; + more recent…]

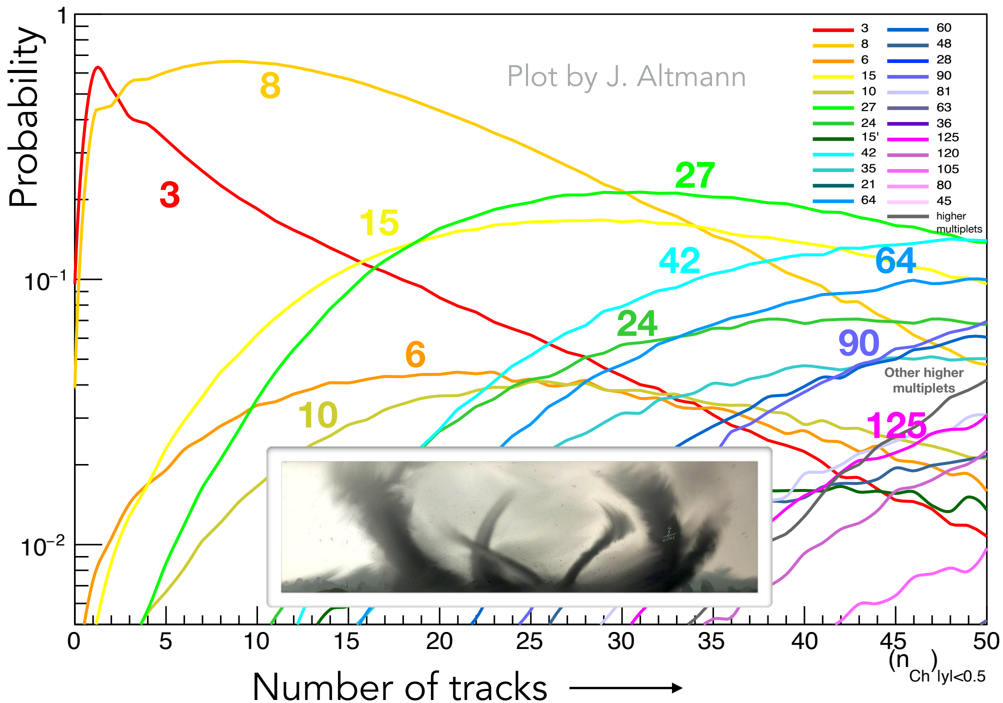
Close-Packing [Fischer & Sjöstrand JHEP 01 **(2017)** 140; Altmann & **PZS** in progress …]

Non-Linear String Dynamics

MPI $\Longrightarrow$ lots of coloured partons scattered into the final states

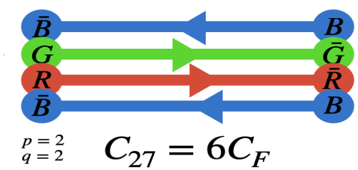
Count **# of (oriented) flux lines** crossing $y = 0$ in pp collisions (according to PYTHIA)

And **classify by SU(3) multiplet:**



Confining fields may be reaching **higher effective representations** than simple $q\bar{q}$ (3) ones.

E.g.: 27



27

$C_{27} = 6C_F$

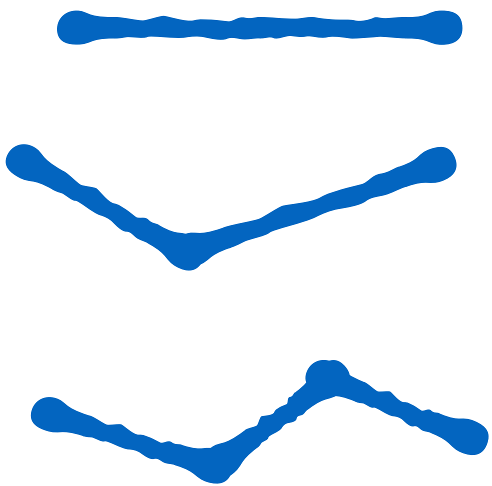
➜ **Is "emergent tension" driving strangeness enhancement in pp?**

Altmann & **PZS** work in progress …

What about Baryon Number?

Types of string topologies:

Open Strings

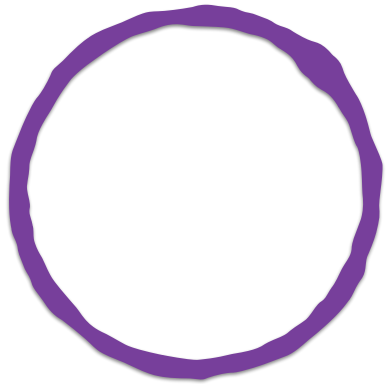


$q\bar{q}$ strings (with gluon kinks)

E.g., $Z \to q\bar{q}$ + shower

$H \to b\bar{b}$ + shower

Closed Strings

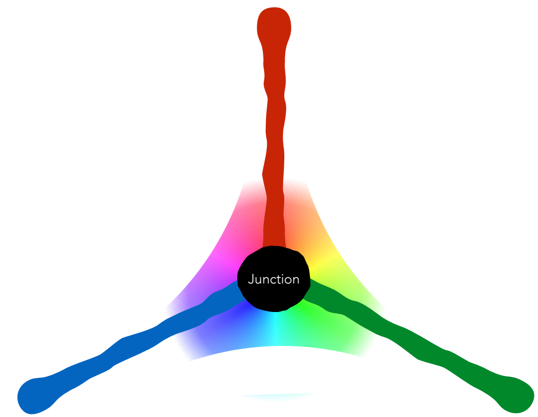


Gluon rings

E.g., $H \to gg$ + shower

$\Upsilon \to ggg$ + shower

SU(3) String Junction



Open strings with $N_C = 3$ endpoints

E.g., Baryon-Number violating neutralino decay $\tilde{\chi}^0 \to qqq$ + shower

Baryon Number Violation & String Topologies:
Sjöstrand & **PZS** NPB 659 **(2003)** 243

String Formation Beyond Leading Colour
Christiansen & **PZS** *JHEP* 08 **(2015)** 003

String Junctions at LHC ?

Altmann & **PZS** in progress
+ Collaboration with M. Kreps, Warwick

Stochastic sampling of SU(3) group probabilities (e.g., $3 \otimes 8 = 15 \oplus 6 \oplus 3$)

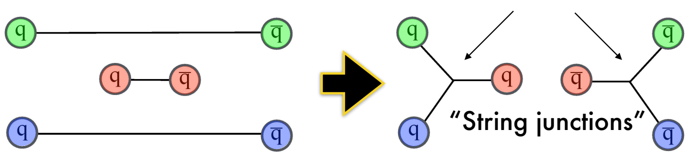
$\Longrightarrow$ Random **(re)connections in colour space** (weighted by group weights)

Christiansen & PZS 2015

Illustration by J. Altmann

For example:

Extra baryon-antibaryon production



Sjöstrand & PZS 2002; Altmann & PZS 2024

New source of low-pT heavy-flavour baryons

Limiting case: one leg is a low-p_T heavy quark

➤ **Heavy-flavour** "Diquarks"

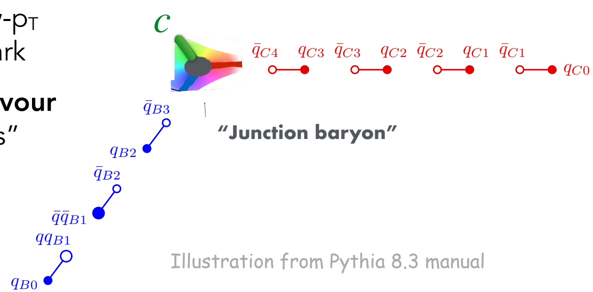
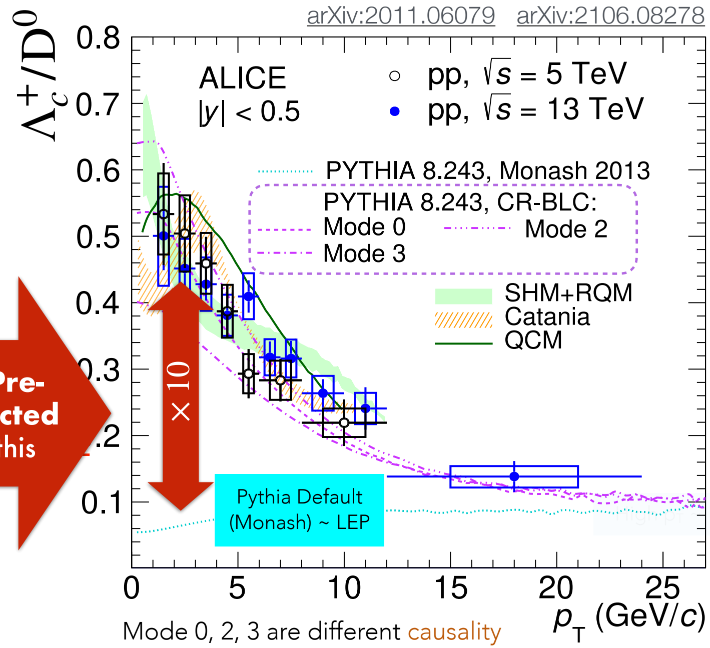


Illustration from Pythia 8.3 manual

Pre-dicted this

ALICE 2021

arXiv:2011.06079 arXiv:2106.08278



Mode 0, 2, 3 are different causality restrictions (0 = none)

Outlook

New insights into perturbation theory at non-trivial orders

NNLO for many hard processes (and N3LO for simple ones)

Several recent showers achieve NLL for arbitrary (IR safe) observables (e.g., PanScales, Alaric)

(& NNLL accuracy not too far, possibly already achieved in evolution variable)

(Off-the-shelf coherent ones: at most NLL (?) in observables ~ evolution variable)

+ New ways to **combine them** (e.g., $\text{MiNNLO}_{\text{PS}}$, VinciaNNLO, Geneva)

→ New Paradigm for Perturbative Calculations: NNLO + NNLL matched MCs

Expect shift from educated guesses to %-level precision (+ theoretically elegant)

New measurements have challenged naive ideas of hadronization

Appears certain we are seeing effects **beyond the static $q\bar{q}$ limit**

But *is it* string interactions / junctions? Is it thermal / QGP? Coalescence? …

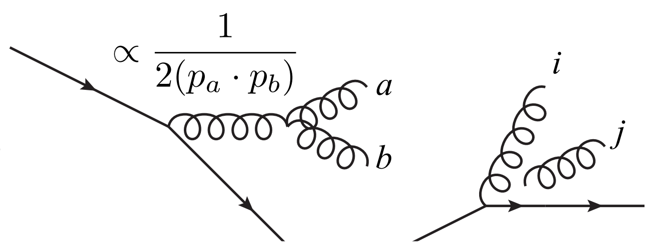
Last shot hasn't been fired …

Extra Slides

Parton Showers: Theory

see e.g PS, *Introduction to QCD*, TASI 2012, arXiv:1207.2389

Most bremsstrahlung is driven by divergent propagators → simple structure



Mathematically, **gauge amplitudes factorize** in **singular limits**

Partons ab → **collinear**:

$$|\mathcal{M}_{F+1}(\ldots,a,b,\ldots)|^2 \stackrel{a||b}{\rightarrow} g_s^2\mathcal{C}\,\frac{P(z)}{2(p_a\cdot p_b)}|\mathcal{M}_F(\ldots,a+b,\ldots)|^2$$

$P(z)$ = **DGLAP splitting kernels**", with $z = E_a/(E_a+E_b)$

Gluon j → **soft**:

$$|\mathcal{M}_{F+1}(\ldots,i,j,k\ldots)|^2 \stackrel{j_g\rightarrow 0}{\rightarrow} g_s^2\mathcal{C}\,\frac{(p_i\cdot p_k)}{(p_i\cdot p_j)(p_j\cdot p_k)}|\mathcal{M}_F(\ldots,i,k,\ldots)|^2$$

Coherence → Parton j really emitted by (i,k) "dipole" or **"antenna" (eikonal factors)**

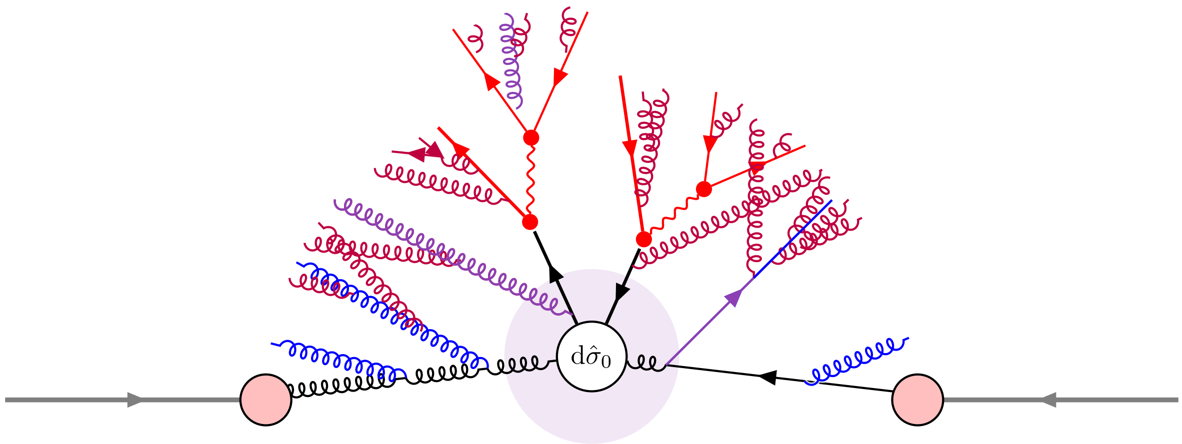
These are the **building blocks of parton showers** (DGLAP, dipole, antenna, ...)

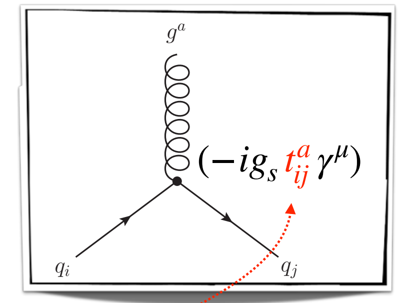
(+ running coupling, unitarity, and explicit energy-momentum conservation.)

What does it mean that two partons are "colour connected"?

Between *which* partons should confining potentials form?

E.g., if we have events with lots of quarks and gluons





Complication:

Every quark-gluon vertex contains an SU(3) Gell-Mann matrix in colour space!

(And $g \to gg$ vertices contain further complicated structures)

➤ **Who ends up confined with whom?**

Colour Tracing

Colour Flow in Event Generators

Event Generators use simplified **"colour flow"** — to trace colour correlations through hard processes & showers ➤ determine which partons end up "colour connected"

Based on SU(N) group product: $N \otimes \bar{N} = (N^2 - 1) \oplus 1$

Fundamental representation (**quarks**) → N

Antifundamental representation (**antiquarks**) → $\bar{N}$

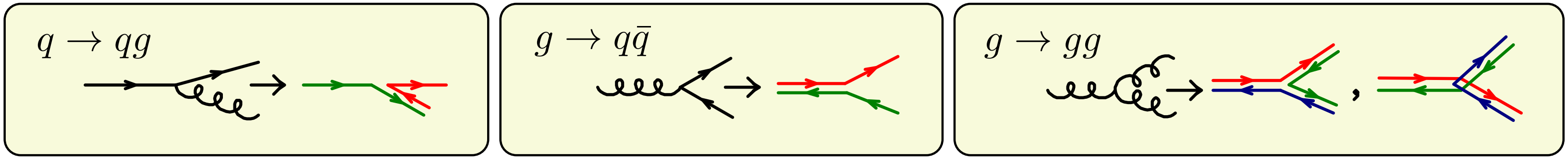
Adjoint Representation (**gluons**) → $(N^2 - 1)$

Singlet (becomes irrelevant for large N) → 1

Thus, for large N ("leading colour"), we can approximate $(N^2 - 1) \sim N \otimes \bar{N}$

LC: gluons → direct products of colour and anticolour; for SU(3) this is valid to ~ $1/N_C^2$ ~ 10%

⇛ Rules for colour flow (= colour-space vertices) in MC Event Generators:

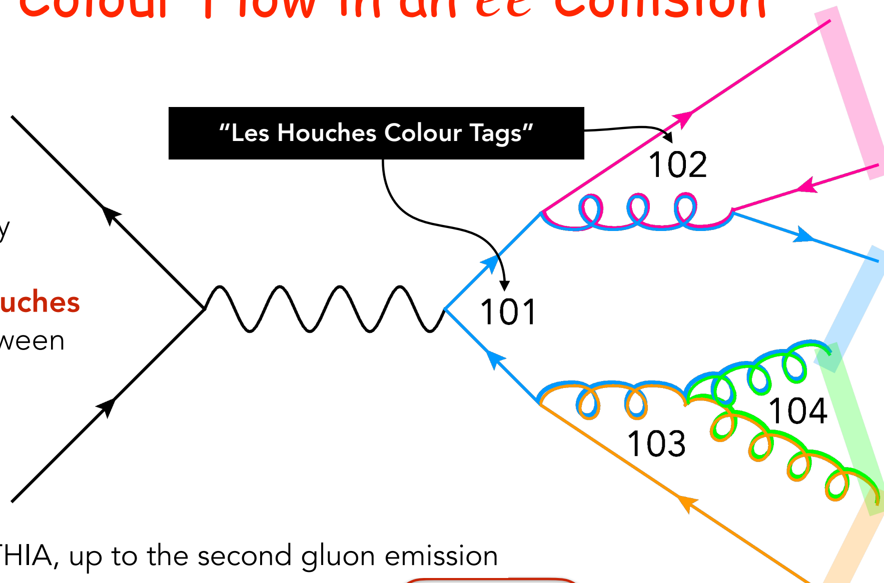


(Note: the "colour dipoles" in dipole and antenna showers are also based on these rules)

LC Colour Flow in an *ee* Collision

MCs: $N_C \to \infty$ limit formalised by letting **each "colour line"** be represented by a **unique Les Houches colour tag**† (no interference between different colour lines in this limit)

†: hep-ph/0109068; hep-ph/0609017



A corresponding event record from PYTHIA, up to the second gluon emission

#	id	name	status	mothers		daughters		colours		p_x	p_y	p_z	e	m
5	23	(Z0)	-22	3	4	6	7			0.000	0.000	0.000	91.188	91.188
6	3	(s)	-23	5	0	10	0	101	0	-12.368	16.523	40.655	45.594	0.000
7	-3	(sbar)	-23	5	0	8	9	0	101	12.368	-16.523	-40.655	45.594	0.000
8	21	(g)	-51	7	0	13	0	103	101	9.243	-9.146	-29.531	32.267	0.000
9	-3	sbar	51	7	0			0	103	3.084	-7.261	-10.973	13.514	0.000
10	3	(s)	-52	6	0	11	12	101	0	-12.327	16.406	40.505	45.406	0.000
11	21	g	-51	10	0			101	102	-2.834	-2.408	1.078	3.872	0.000
12	3	s	51	10	0			102	0	-10.246	17.034	38.106	42.979	0.000
13	21	g	52	8	0			103	101	9.996	-7.366	-28.211	30.823	0.000

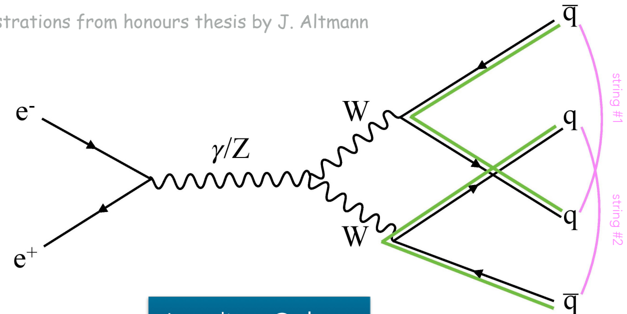
Colour Reconnections? (CR)

NB: much more important in LHC collisions ➜ next lecture

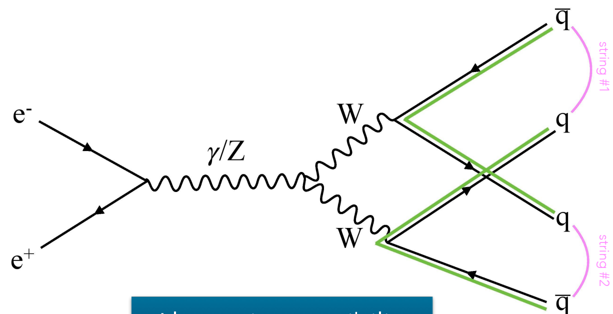
Consider two (uncorrelated) parton systems

Textbook example: $e^+e^- \to W^+W^- \to \text{hadrons}$

Illustrations from honours thesis by J. Altmann



Leading Colour



Alternative possibility

Probability for uncorrelated $q\bar{q}$ pair to **accidentally** be in colour-singlet state follows from $3 \otimes \bar{3} = 8 \oplus 1$ ☛ 1 in 9 ☚ = $1/N_C^2$

With a probability of 1/9, both options should be possible (remaining 8/9 allow LC only)

Choose "lowest-energy" one (cf action principle) (assuming genuine quantum superpositions to be rare.)

➜ small shift in W mass ("string drag") (➜ now important for top quark mass at LHC)

LEP-2: No-CR excluded at 99.5% CL [Phys.Rept. 532 (2013) 119; arXiv:1302.3415]

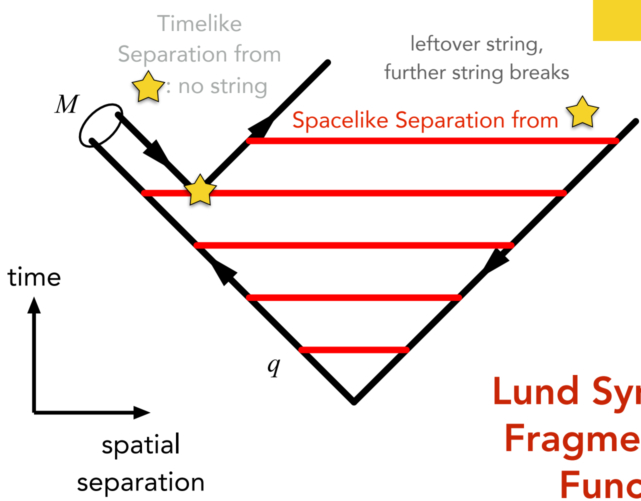
Measurements consistent with $\sim 1/N_C^2$ expectation but not much detailed information.

The String Fragmentation Function (in momentum space)

Consider a string break ☆, producing a meson M, and a leftover string piece

The meson M takes a fraction z of the quark momentum,

Probability distribution in $z \in [0,1]$ parametrised by **Fragmentation Function**, $f(z, Q^2_{\mathrm{HAD}})$



Observation: All string breaks are **causally disconnected**

Lorentz invariance $\Longrightarrow$ string breaks can be considered in *any order*. Imposes "left-right symmetry" on the **FF**

$\Longrightarrow$ **FF** constrained to a form with **two free parameters**, a & b: constrained by fits to measured hadron spectra

Lund Symmetric Fragmentation Function

$$f(z) \propto \frac{1}{z}(1-z)^a \exp\left(-\frac{b(m_h^2 + p_{\perp h}^2)}{z}\right)$$

Supresses high-z hadrons (↑ a)

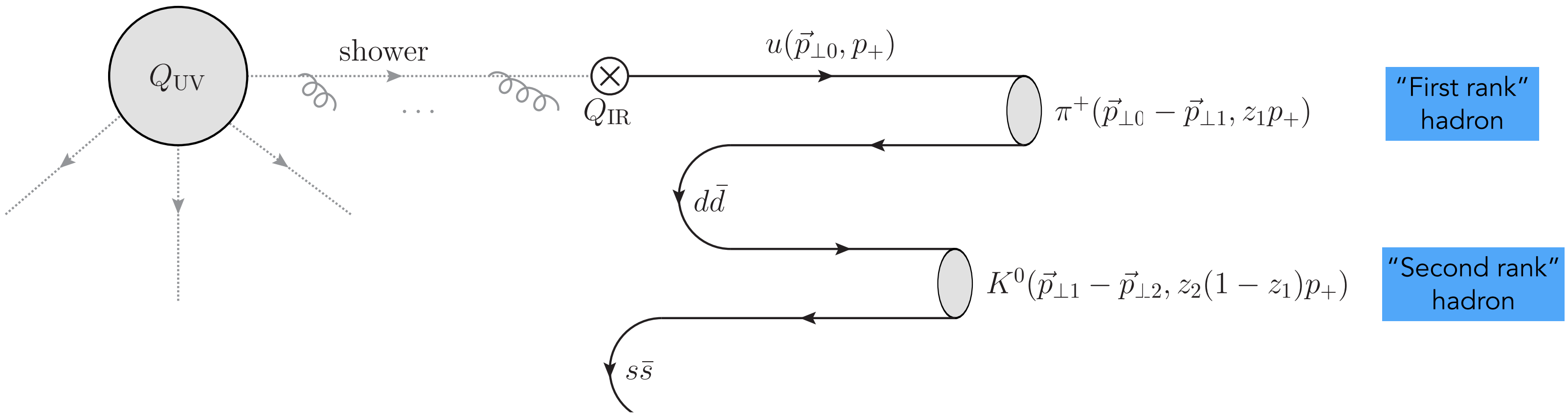
Supresses low-z hadrons (↑ b)

Will return to illustrations of these parameters later (tuning)

Iterative String Breaks (in momentum space)

Recall: String breaks are causally disconnected → May iterate from outside-in

Note: using light-cone momentum coordinates: $p_+ = E + p_z$



On average, expect energy* of n^th "rank" hadron to scale like ~

$$E_n \sim \langle z \rangle (1 - \langle z \rangle)^{n-1} E_0$$

*) more correctly, the p_+ light-cone momentum coordinate

A simple prediction: constant rapidity density of hadrons along string

Rapidity

$$y = \frac{1}{2}\ln\left(\frac{E+p_z}{E-p_z}\right) = \frac{1}{2}\ln\left(\frac{(E+p_z)^2}{E^2-p_z^2}\right) \rightarrow \ln\left(\frac{2E}{m_\perp}\right)$$

(in limit of small $m_\perp = \sqrt{m^2+p_\perp^2} \ll E$)

Recall: **expect energy of n[th] "rank" hadron** $E_n \sim \langle z\rangle(1-\langle z\rangle)^{n-1}E_0$

$$\implies y_n \sim y_1 + (n-1)\ln\big(1-\langle z\rangle\big)$$

Rapidity difference between two adjacent hadrons:

$$\Delta y = y_{n+1} - y_n \sim \ln\big(1-\langle z\rangle\big)$$

$\longleftarrow$ Constant, independent of n (and of E_0)

Predicts a flat (uniform) rapidity "plateau" (along the string axis):

Also called **"Lightcone scaling";** this is exactly what is observed in practice.

The Rapidity Plateau

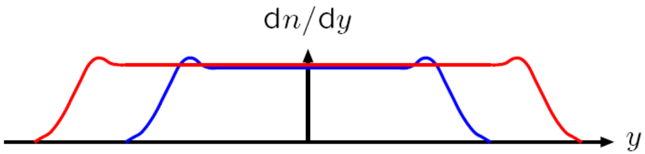
Expect ~ flat Rapidity Plateau along string axis

Estimate of rapidity range for fixed E_q:

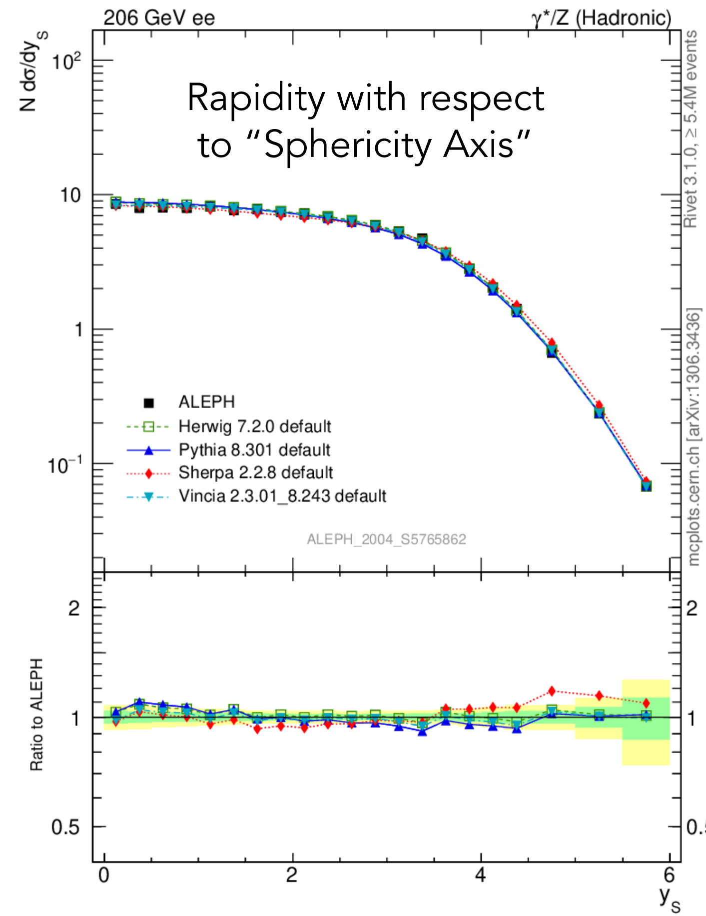
$$\langle y \rangle_1 \sim \ln\left(\frac{2\langle z\rangle E_q}{\langle m_\perp \rangle}\right)$$

~ 5 for $E_q \sim 100$ GeV, <z> ~ 0.5, and $\langle m_\perp \rangle \sim 0.5$ GeV

Changing $E_q \Longrightarrow$ logarithmic change in rapidity range:



$\langle n_{\mathrm{ch}} \rangle \approx c_0 + c_1 \ln E_{\mathrm{cm}}$, ~ Poissonian multiplicity distribution



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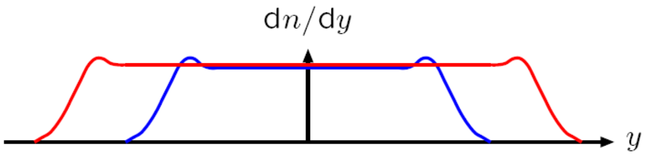

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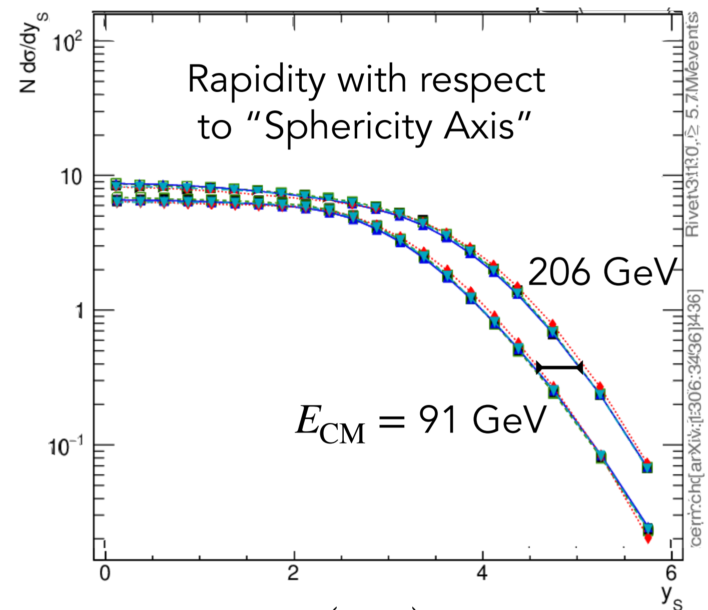


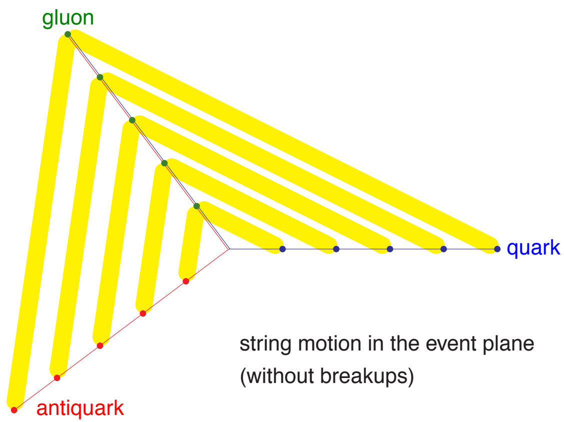
$$\ln\left(\frac{206}{91}\right) = 0.8$$

Actual difference is smaller ⟼ ~ 0.5

(some energy also goes to increase particle production in the central region, **3-jet events**)

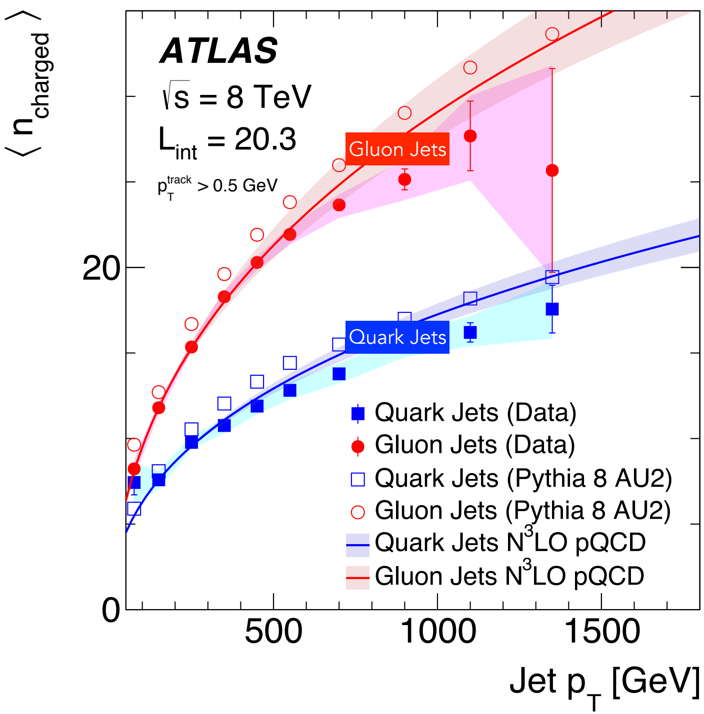
Gluon Kinks: The Signature Feature of the Lund Model

Gluons are connected to **two** string pieces



Each quark connected to **one** string piece

Expect factor ~ 2 ~ C_A/C_F more particles in gluon jets



Important for discriminating new-physics signals

Decays to **quarks** vs decays to **gluons**,

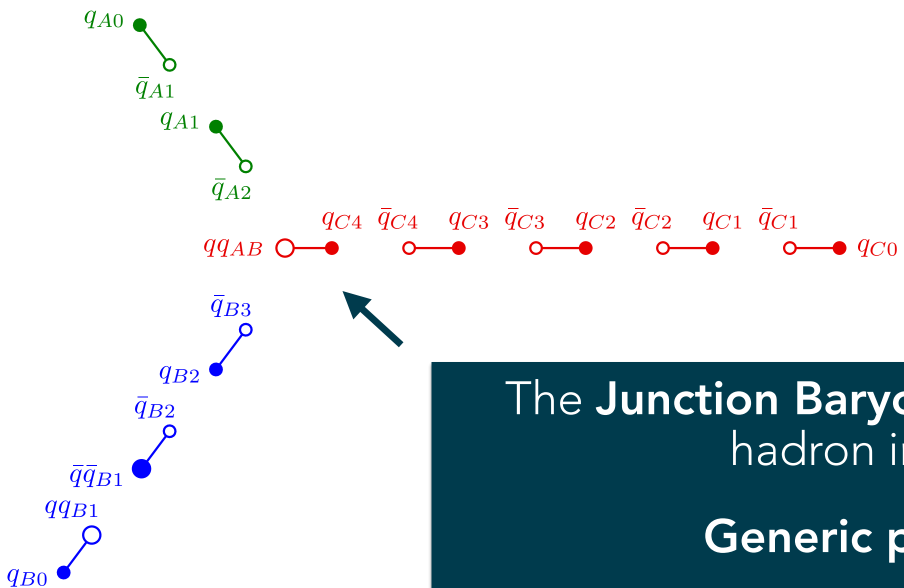
vs composition of **background** and **bremsstrahlung** combinatorics

See also
Larkoski et al., JHEP 1411 (2014) 129
Thaler et al., Les Houches, arXiv:1605.04692

What do String Junctions do?

Assume Junction Strings have same properties as ordinary ones (u:d:s, Schwinger p_T, …)

➤ No new string-fragmentation parameters



[Sjöstrand & **PS**, NPB 659 (2003) 243]
[+ J. Altmann & **PS**, in progress]

The **Junction Baryon** is the most "subleading" hadron in all three "jets".

Generic prediction: low p_T

A Smoking Gun for String Junctions: **Baryon enhancements at low p_T**

LHCb: also in Bottom

Λ_b asymmetry

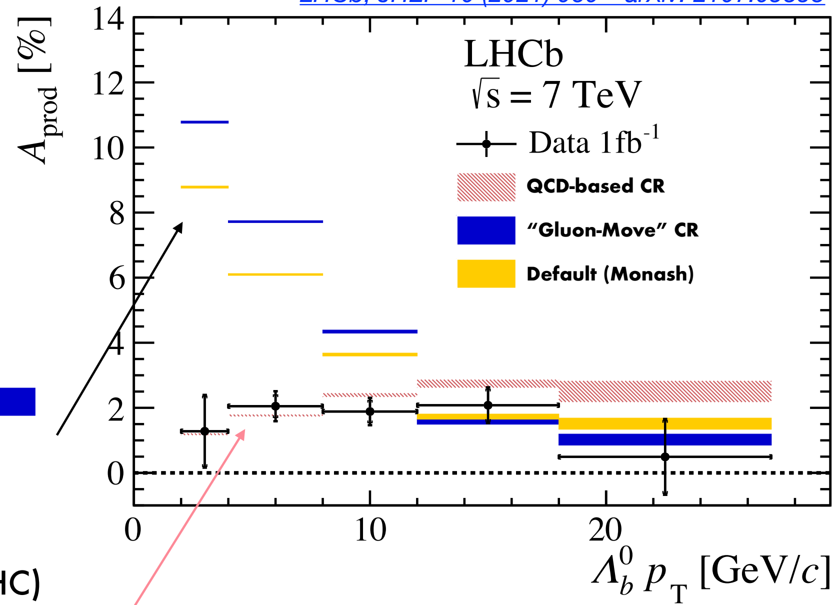
$$A = \frac{\sigma(\Lambda_b^0) - \sigma(\overline{\Lambda}_b^0)}{\sigma(\Lambda_b^0) + \sigma(\overline{\Lambda}_b^0)}$$

Baseline Expectations: &

b quark combines with the proton beam remnant $\Longrightarrow \Lambda_b$ production

Not possible for $\bar{\Lambda}_b$ (no $\bar{p}$ remnant at LHC)

LHCb, JHEP 10 (2021) 060 • arXiv: 2107.09593



QCD CR with "string junctions" [Christiansen & Skands JHEP 08 (2015) 003]

Adds large amount of low-p$_T$ Λ_b and $\bar{\Lambda}_b$, in equal amounts. Dilutes asymmetry!